LIGHTING GLOBAL
Catalyzing markets for modern off-grid lighting
AN INNOVATION OF WORLD BANK GROUP
THE WORLD BANK IBRD • IDA
IFC International Finance Corporation

Technical Notes

Issue 21 June 2015

Integrating Sphere Measurement Part II: Calibration

This Technical Note is Part II in a three part series examining the proper maintenance and use of integrating sphere light measurement systems. This second Note covers calibrations and auxiliary measurement details necessary to achieve technically valid results with an integrating sphere system.

This article builds on previous Technical Notes available at www.lightingglobal.org

Introduction

The accurate operation of an integrating sphere system is challenging and requires proper calibration and test setup procedures to produce technically valid test results. Many light sources do not have consistent and repeatable outputs, which can make measurement errors difficult to identify. Total luminous flux measurements can be time consuming, which can encourage operator error. In practice, these and many other factors contribute to the difficulty of correctly using an integrating sphere measurement system. This Technical Note will focus on several important elements of sphere operation, including: the proper calibration of an integrating sphere, the auxiliary lamp (AUX) correction process for mitigating lamp substitution errors, and detector response details.

Calibration

The first step in preparing a sphere to make flux measurements is calibration (Figure 1). A sphere is calibrated by taking a measurement of a lamp standard with a known flux output. This establishes the absolute detector response of the system to a specific flux input, and captures the flux from the lamp standard *plus* the influence of the lamp holder, mounting post, baffles, ports, and any other hardware present during the test.

The lamp standard itself is a crucial element of the system. Lamp standards are typically quartz tungsten halogen (QTH) lamps that are seasoned and hand selected for stability and repeatability. The accurate calibration and measurement results of an integrating sphere system are directly tied to the lamp standard used for the calibration. The lamp standard must have a stable, repeatable output.

Lamp standards are supplied with a lamp file that is used by system software during the calibration process. The lamp file needs to be in a format compatible with the photometric software used by the system and frequently lists photometric quantities like total luminous flux, correlated color temperature, and chromaticity coordinates. When used with a spectrometer, the file also needs spectral flux data that lists the radiometric output (usually in milliwatts) for each wavelength between 380-780 nm. The lamp file typically lists the outputs in 1 or 5 nm increments.

QTH lamps are fragile and may be damaged by rough handling or improper power applied to the lamp filament. Lamps should only be handled with clean gloves to avoid oil deposits from fingers on the bulb wall. Lamp standards should be powered ON and OFF by slowing ramping the current (a 30-second ramp time is sufficient) to avoid thermal shocks to the filament as it heats and cools. The QTH should be allowed to stabilize (warm up) for 10-15 minutes before measurements are taken. The filament in a QTH lamp is the most delicate when it is hot, and a lamp standard should never be moved or bumped while it is powered ON and should be allowed to cool for several minutes before handling after the lamp is powered OFF.

Lamp standards are often supplied with a custom power supply configured to correctly ramp and power the lamps. They can also be powered from a standard laboratory power supply controlled by a computer (to properly ramp the power) if the power supply is capable of accurately supplying the required power. A 4-wire power supply setup should be used when manually powering a lamp standard (a 4-wire measurement uses two wires to supply current to the lamp and two wires to measure the voltage directly at the lamp leads).

Sphere calibrations should be performed at regular intervals depending on the frequency of testing and the required confidence in the test results. Weekly calibration is recommended for labs with steady test schedules. Any changes to the sphere equipment, including moving a fiber optic spectrometer cable, should trigger a fresh calibration.

Laboratories are encouraged to acquire and use a set of three (3) lamp standards to maintain the calibration of their integrating sphere system. This allows the calibration from each lamp to be cross-referenced to the calibrations from the other two lamps. The procedure to do this can vary depending on the system software, but the basic concept requires a stable, repeatable light source that can be measured with all three calibrations. If one lamp standard has drifted (and therefore fallen out of calibration), the other two standards will agree on the measurement and the drifted lamp will not.

Lamp standards are commonly rated for 50 hours of operation and test laboratories should keep a log of the runtime for their standards. In order to minimize burn hours or the possibility of damage to expensive primary standards, a second set of lamp standards, created by the test lab from their primary lamp standards, can be made and used for frequent calibrations or training of inexperienced personnel. If test results show inconsistencies or become questionable, the primary standards can then be used for fresh calibration and retesting.

Lamp substitution

When a calibration is performed, the system software uses the standard lamp file to establish the relationship between the flux inside the sphere and the detector response. Once established, other DUT's (device under test) may be placed in the sphere, powered ON, and measured by reading the detector signal. The software compares the DUT detector signal to the lamp standard detector signal and uses a linear interpolation to calculate the absolute DUT output. This process is known as *lamp substitution*.

Auxiliary (AUX) corrections

When a calibration is performed with a lamp standard, the detector signal is a function of the flux emitted by the lamp standard AND the specific sphere throughput during the test. The throughput, in turn, is influenced by the self-absorption from the lamp holder and any hardware (wires, connectors, etc.) inside the sphere. When another DUT is placed in the sphere, the throughput will necessarily change due to differences in the self-absorption of the DUT housing and any hardware changes. In order to account for this change in throughput, a second 'auxiliary' lamp is used to measure the relative change in sphere throughput between the lamp standard test and the DUT test.

An AUX test is a relative measurement of the sphere throughput under two conditions: the throughput with the lamp standard hardware, and the throughput with the DUT hardware. The AUX lamp illuminates the sphere while detector readings are taken in each condition. A correction factor can then be applied to DUT measurements that accounts for the change in sphere throughput from the DUT housing and any additional hardware placed inside the sphere and used for the test. The correction factor should be *spectral.* This means each wavelength interval should be corrected separately to account for the variable reflection of different colors from strongly colored DUT housings. Many spectroscopy software programs manage the AUX correction process automatically by guiding the user through the acquisition, storage, and application of the AUX correction files.

The AUX correction process relies on an equivalent light output from the AUX lamp when measurements are made of the lamp standard and DUT. When an AUX measurement is stored in software for the lamp standard and subsequent AUX DUT measurements are made at a later date, it is possible that the flux from the AUX lamp will be different and an error will be induced in the AUX correction. The size of this error will likely be small in most cases and acceptable for general testing. To minimize this error, however, the lab should test both the AUX lamp standard and AUX DUT setups at the same time without turning OFF the AUX lamp.

The AUX correction process can be demonstrated and verified with a simple experiment (Fig. 2 below). A stable DUT light source is placed in the sphere with a sequence of different colored paper samples used to change the self-absorption of the sphere environment. The light inside the sphere stays the same, while the colored paper changes the self-absorption. If done properly, AUX measurements can correct for the colored paper and produce consistent flux measurements. If flux measurements are the same with and without the colored paper (after the AUX corrections are applied), then the AUX correction is working properly.

Detector response

When a light source is placed inside a sphere and powered ON, the detector produces a signal that is proportional to the amount of light flux that falls on the detector receiver window. The detector response is directly proportional to the flux at the detector window – increasing the flux will increase the detector response. The flux at the detector window is a function of:

- the light produced by the light source
- the throughput of the sphere system
- the self-absorption of the DUT

In order to produce technically valid test results with an integrating sphere system, the technicians performing the tests and managing the equipment must understand how the detector and integrating sphere hardware work together to produce the signal that is interpreted by system software and used to calculate the absolute properties of the DUT light source.

Spectrometer operation

The term ‘spectrometer’ refers to any of a number of devices used to analyze the spectral characteristics of light radiation. When a spectrometer is calibrated and used in a system to measure the absolute flux from a light source, it is properly called a ‘spectroradiometer’. The lighting industry, however, more commonly uses the term spectrometer to describe these types of measurements and so too will this Technical Note.

A typical spectrometer uses a series of optical elements to image a light source onto a charge-coupled device (CCD) array. In an integrating sphere system, light from a detector window placed on the interior wall of the sphere is coupled to the spectrometer by a fiber optic. The incoming light flux is diffracted onto the CCD array as discrete wavelengths. This allows the relative power of each wavelength in the light source to be measured.

CCD arrays work by measuring each individual pixel (which corresponds to a specific wavelength of light) in a number of ‘counts’. The counts are based on a pixel voltage generated by the incoming photons. The array is set to an exposure time where the counts of each pixel are recorded, then the array is reset and the exposure is repeated. The exposure is set, either manually by the operator or automatically by the system software, to optimize the light signal on the CCD array without saturating any particular pixel. A pixel becomes saturated when the exposure time is too long and the voltage on the pixel hits a maximum. When a pixel is saturated, additional counts are lost for that wavelength and the measurement is no longer valid.

Software uses the raw data from the spectrometer to calculate the spectral radiometric power, or ***spectral power distribution (SPD)***, of the light source in squared microwatts per nanometer (uW/nm)[1]. The photometric quantities of lumens, CCT, CRI, chromaticity etc. are then calculated from the SPD.

Photometer operation

Photometer type detectors used for integrating sphere measurements have become less common with the advent of LED lighting technologies and the availability of low cost spectrometer-based systems. They are, however, still very capable of performing these measurements. A photometer uses a semiconductor element (typically a photodiode) to produce a voltage signal as a response to incoming light. In an integrating sphere, a detector window is placed on the sphere wall and the photodiode and support electronics are just behind this window in a small optical cavity. Basic photometers capture total luminous flux, while others

---

[1] may also be W/nm or mW/nm

with multiple semiconductor elements are able to capture color data as well.

The detector window is responsible for collecting the flux from the inside of the sphere with a cosine response AND is also responsible for filtering the light to perform a V(λ) correction (Figure 3). Thus, the detector window itself physically corrects for human visual perception. This can lead to errors when measuring LED sources if the filter does not provide an accurate V(λ) response. This is of particular concern in the blue portion of the visible spectrum where there is a peak in a typical LED light source and where photometer filters used for photometric correction are less accurate and more prone to spectral mismatch.

Background (dark) readings

The detector signal from a photometer or a spectrometer will include a certain amount of electrical noise. This comes from the system electronics, thermal energy in the detector elements, and any stray light that might enter the sphere from the outside through small openings in the seal between the two sphere halves. This background noise must be subtracted from any measurements made in the sphere.

For spectrometer detectors, the background reading will be proportional to the exposure time for each DUT, which in turn is proportional to the DUT flux. This means that a background reading must be taken for different flux inputs to the sphere. Some spectrometer software systems handle the management of background readings automatically by taking a series of (dark) readings at the beginning of a measurement session and then applying these readings accordingly. Other systems require the operator to manage background readings manually.

All electric light sources require some amount of time to stabilize when they are turned ON. This can be a burden during testing, specifically when a background (dark) reading is required and the DUT light source is already ON and stabilized. For this reason, some spectrometer systems incorporate a physical shutter inside the spectrometer housing or placed in line with the fiber optic cabled that connects the sphere detector window to the spectrometer. This arrangement is strongly recommended for sphere systems testing pico-powered lighting products.

Photopic vs. Radiometric measurements

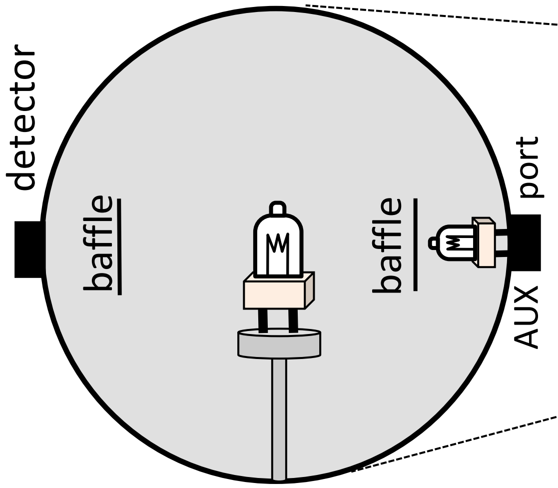
Radiant energy in the electromagnetic spectrum can be measured and quantified in **radiometric** units of watts (= Joules/sec). Our eyes, however, only perceive certain wavelengths of this radiant energy as visible light. Furthermore, our eyes see some wavelengths better than others, with peak sensitivity in the green portion of the visible spectrum. The visible spectrum spans 380-780 nanometers (nm), with peak sensitivity occurring at 555 nm.

The **lumen** is a numeric quantity of light based on the human eye's visual ability to see that light. The number, or quantity, of lumens from a particular light source is calculated by measuring the radiometric energy and scaling, or weighting, this energy by the sensitivity of a human 'standard observer'. This 'luminous efficiency function' is called the **V-lambda (V(λ)) curve** and is used to convert **radiometric units** into **photometric units**. Any discussion of light that includes photometric terminology will involve a human weighting function (V(λ) or V'(λ)). Discussions of light in terms of energy or watts will be radiometric in nature.

Luminous efficiency function V(λ)

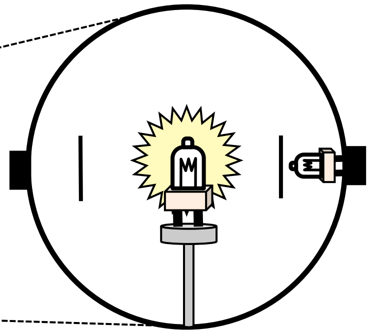
Figure 3. Radiometer and photometric units

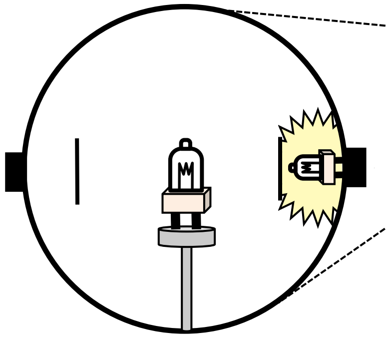
Figure 1. Sphere calibration procedure



① Calibration starts with a background (dark) reading. A background reading is subtracted from each measurement. When the exposure time (for spectrometer detectors) is changed, a new background measurement is necessary. Background readings can be taken for a range of exposure times at the beginning of a session and used as needed to match the exposure times of different DUT measurements. Some software programs handle background readings automatically, while others require manual loading.

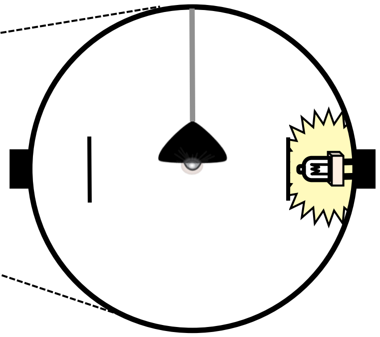
② The lamp standard is powered ON and allowed to stabilize (10 – 15 minutes for most quartz tungsten halogen (QTH) lamps). A reading is taken and matched to a lamp file in software. This establishes the relationship between the sphere throughput and a known input flux. Lamp standards are gradually powered (ramped) ON and OFF slowly and handled with care to avoid damage that could affect the calibration.

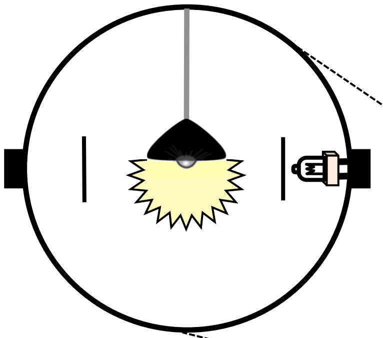




③ The lamp standard is powered OFF and the AUX lamp is powered ON and allowed to stabilize. **A new exposure time and background reading are set.** This AUX measurement establishes a baseline for the self-absorption of the lamp standard and lamp holder hardware.

④ The AUX lamp is left ON and the DUT is placed in position. An AUX reading is taken and used by software to correct for the change in self-absorption that occurs with a change in the sphere throughput.





⑤ The AUX lamp is powered OFF and the DUT is powered ON and allowed to stabilize. **A new exposure time and background reading are set.** The DUT is now ready to be measured. The AUX measurement for this DUT can be used for all samples that have **identical** housing and hardware setups. Any changes will require a new AUX reading, including a new AUX reading for the lamp standard and lamp holder.

Auxiliary correction experiment

A laboratory can check the accuracy of its auxiliary corrections by placing colored sheets of paper in the sphere while keeping the input flux from an LED light source constant (Figure 2). The colored sheets will change the sphere throughput but NOT change the actual input flux from the LED source. A simplified procedure is given here:

- Place an LED source in the sphere.
- Turn ON the AUX lamp and allow it to stabilize (10-15 minutes).
- Take an AUX baseline reading.
- Place colored sheets of paper, one at a time, under the LED source. Take an AUX reading for each color.
- Turn OFF the AUX lamp and power ON the LED source allow it to stabilize.
- Measure the baseline flux without any sheets of paper.
- Place the different colored sheets, one at a time, under the LED source and take a flux measurement for each color. Use the appropriate AUX correction for each color.
- Compare the measurements for each color. Different measurement values indicate errors in the AUX corrections.

The flux inside the sphere remains constant, so the AUX corrections *should* enable the same flux measurement for each color. If the various colored sheets of paper change the flux measurement, then the system's AUX correction is not functioning properly.

NOTE: Integrating sphere software programs handle AUX corrections differently. The test procedure should be adjusted appropriately.

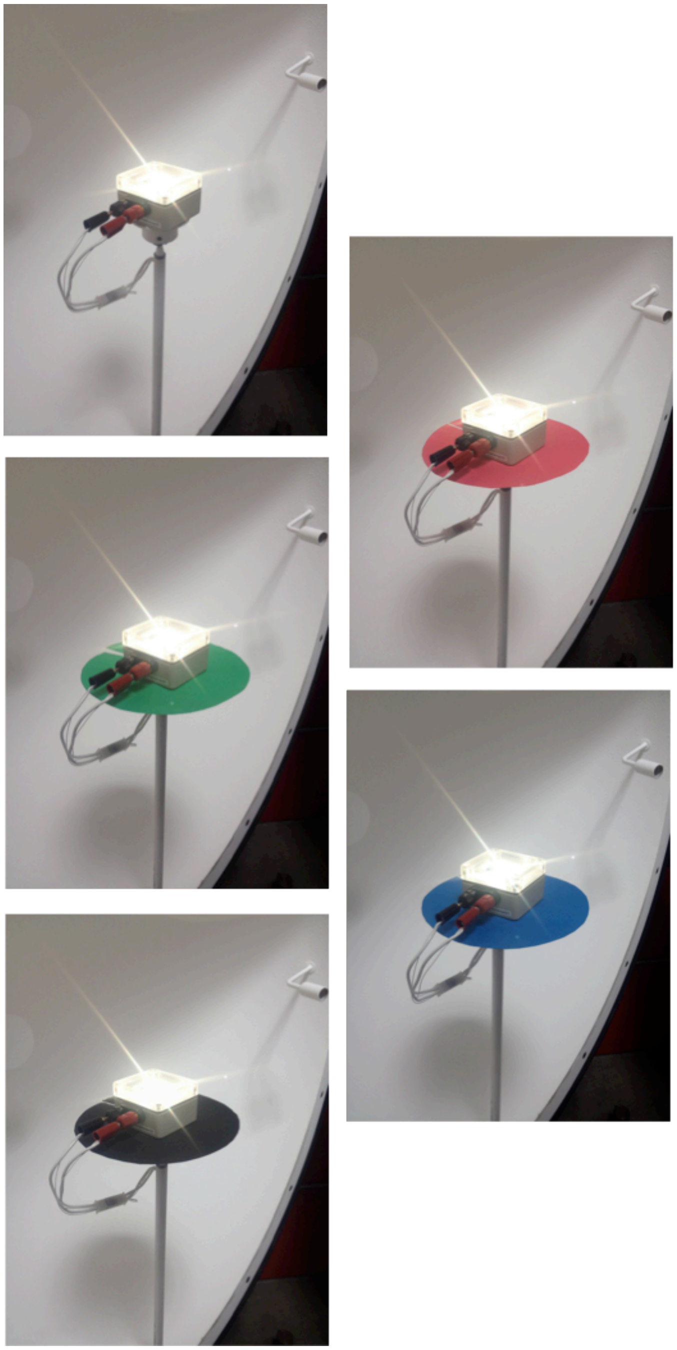


Figure 2. An experiment to check the AUX correction accuracy of an integrating sphere system. The input flux from the LED light source remains constant while the sphere throughput changes with different colored sheets of paper. Proper AUX correction can account for these changes.